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Garnet megacrysts of the Williams diatremes, north-central Montana

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Abstract

The garnet megacrysts from the Williams diatremes in north-central Montana range in length from 1 to 4.5 cm; they are dominantly red orange in color and pyropic in composition. The Cr content of all the megacrysts is low (Cr_2O_3 less than 2.5 wt%). The only correlation found between the physical characteristics and the composition of the megacrysts relates deep red color to high Cr content. Compositions of coexisting clinopyroxenes suggest that the garnet megacrysts formed at mantle conditions similar to those estimated for coexisting garnet peridotite xenoliths from the Williams diatreme. The garnet megacrysts from the Williams diatreme are similar in composition to garnet megacrysts from other kimberlites worldwide. The compositional range of Williams megacrysts is as large as combined compositional ranges of megacrysts from Africa and North America.

Introduction

Megacrysts (also called "discrete nodules") are one of the five types of upper mantle nodules found in kimberlite (Harte, 1978). They are distinctive monomineralic inclusions with a minimum size of 1 cm in the largest dimension (Eggler et al., 1979). Megacrysts are typically rounded single crystals; less commonly, they can be multigranular aggregates of a single mineral. Inclusions in megacryst minerals are uncommon but are valuable for determining equilibrium assemblages.

In kimberlites, garnet, clinopyroxene, orthopyroxene, ilmenite, phlogopite, and olivine may form megacrysts. Megacrysts can be an important component of the assemblage of tracer minerals that is widely used in prospecting for kimberlites. The presence and abundance of megacrysts are used in locating kimberlitic dikes and pipes. The compositions of some megacryst phases indicate the depths of origin for the megacrysts, and knowledge of those conditions is useful for making inferences about the diamond potential of a specific kimberlite pipe.

The megacryst suite from the Williams diatremes consists of single discrete grains of garnet, rare clinopyroxene, olivine (commonly serpentinized), and phlogopite. The garnets are by far the most abundant megacryst in the Williams diatremes; they are abundant enough to constitute a statistically reasonable group from a single location. Recognition of a correlation between a readily observable physical characteristic and composition may identify a characteristic that can be easily used in the field to indicate garnet megacryst composition.

Locality

The Williams diatremes are in north-central Montana on the edge of the Missouri River Breaks region; they are part of a swarm of diatremes trending east–northeast (Hearn, 1979). The Williams group of diatremes consists of three poorly exposed kimberlitic pipes (Williams 1, 2, 3) and a kimberlitic dike (Williams 4) (Hearn and Boyd, 1975; Hearn and McGee, 1984). The garnet megacrysts were collected from the Williams 4 dike and in the area immediately surrounding the dike; most were found in alluvial and colluvial deposits. In addition, a few megacrysts were picked out of hard portions of the dike. Some additional megacrysts were obtained from concentrate taken from a trench dug across the Williams 4 dike.

The collection

The Williams garnet megacryst collection consists of 179 garnets, chosen either because they were conspicuously large or because they were longer than 1 cm and were present in several selected 1 to 2 m^2 areas near the Williams 4 dike. Although some megacrysts appear to be broken, most are spheroidal and have smooth surfaces, with varying amounts of fine-grained reaction rim attached (kelyphitic coating). To the naked eye, all appear dark, primarily because of multiple internal fractures that absorb light and because thin edges, which show color well, are rare. Physical characteristics such as dimensions, color, and outward appearance were recorded for all megacrysts in order to determine if any correlations exist between the readily observable features and the compositions of the megacrysts. Megacrysts possessing representative physical characteristics were selected for microprobe analysis.

Physical characteristics

The garnet megacrysts are predominantly subrounded; many have indentations and slightly irregular shapes. In general, the surfaces of the garnets are smooth, and, as is typical among garnet megacrysts from other kimberlites, none of them is euhedral. A number of the megacrysts have a fracture surface and apparently are incomplete.

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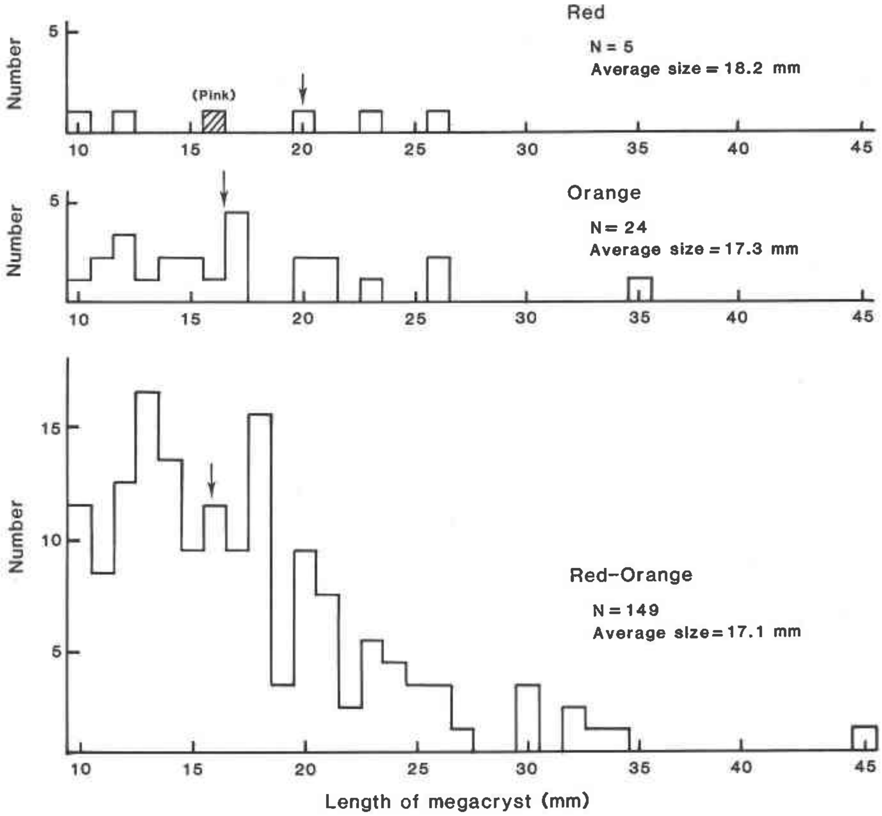

Fig. 1. Histograms of Williams garnet megacryst sizes, grouped by garnet color. Arrows indicate mean size for each group.

These samples were included in the collection only if the existing portion fit the minimum size criterion for megacrysts. All of the megacrysts have some internal cracks and fractures; a few have so many fractures that they appear granular or sugary in texture.

Size

Size, defined by three perpendicular measurements, was determined for each megacryst. Partial measurements were made on samples embedded in dike material or in autoliths. The three dimensions measured were defined as follows: longest dimension = length, intermediate dimension = width, and shortest dimension = thickness. Length was used to define size groups. The largest megacryst in the Williams collection is 4.5 cm long; the average-size megacryst is 1.7 cm; but 70% of the megacrysts are concentrated in the 1.0- to 2.0-cm size range. A histogram (Fig. 1) shows the size distribution within each of the three color groups.

Shape

Shapes were categorized by using ratios of width to length and thickness to width, as plotted in the fields defined by a Zingg plot (Fig. 2). The garnet megacrysts range from rounded blocks to flat disks; most are disk shaped (i.e., width/length > 0.67 and thickness/width < 0.67). Spherical and bladed shapes are about equally abundant, but both are less common than disk shapes; rod-like shapes are the least common.

Color

Colors of the megacrysts were determined with the techniques discussed in Hearn and McGee (1983). Internal

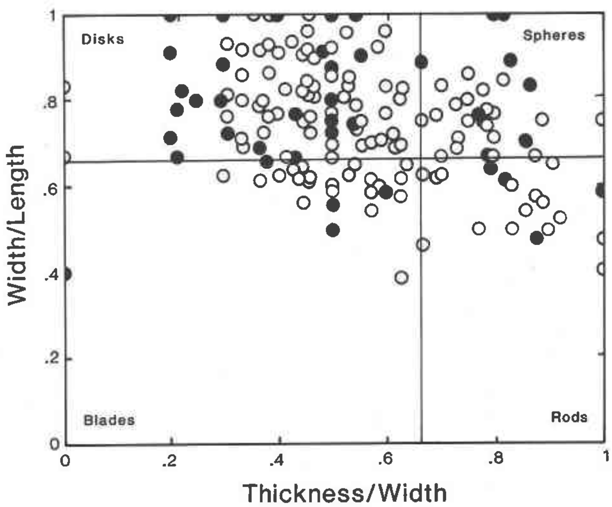

Fig. 2. Zingg plot showing shapes of megacrysts. Filled circles are analyzed megacrysts.

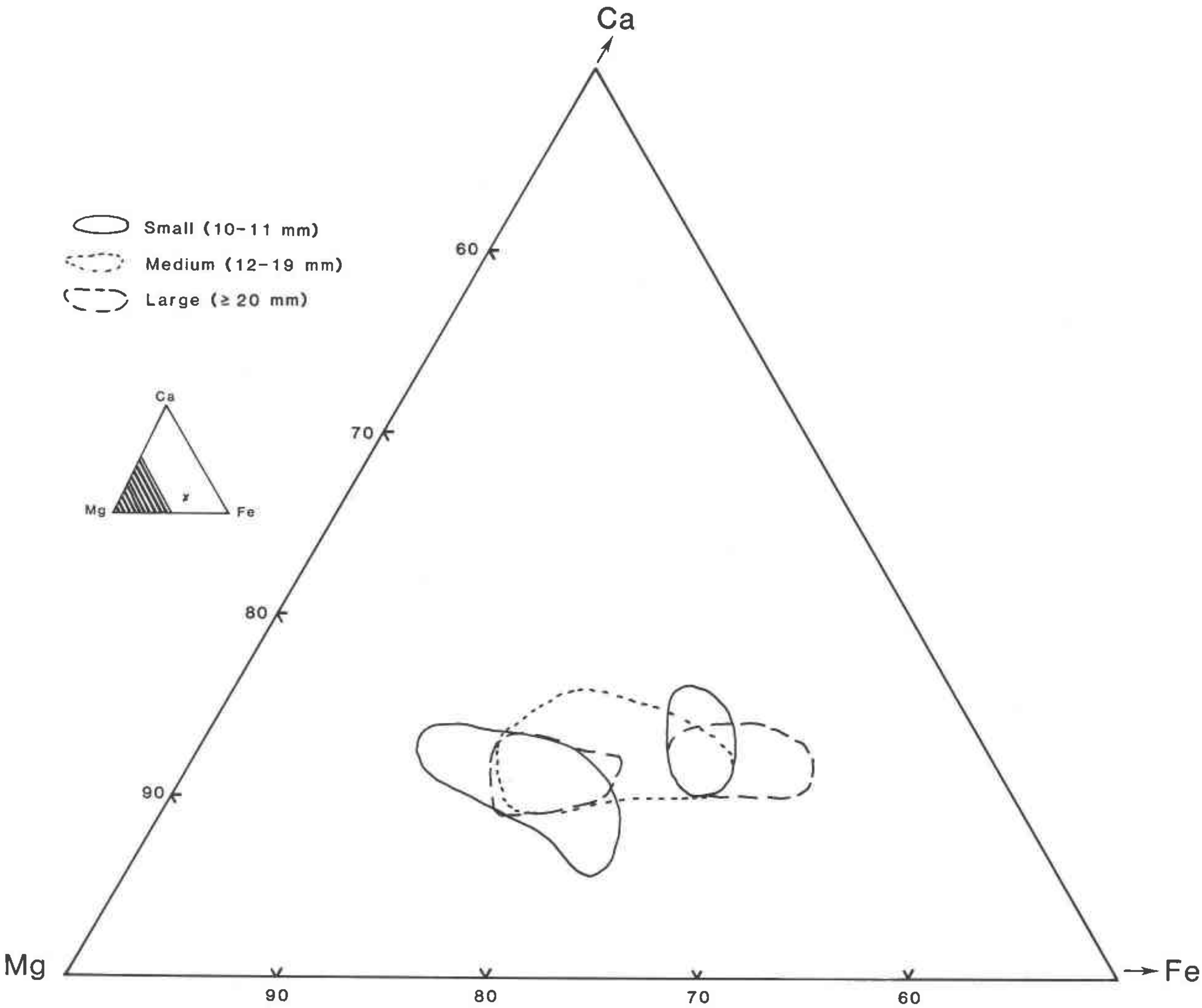

Fig. 3. Mg corner of the Ca-Mg-Fe ternary diagram for Williams garnet megacrysts, grouped by size. Inset shows composition of one Fe-rich megacryst (indicated by "x").

fractures and the presence of coatings on some of the samples hampered determinations of color, so small pieces of some megacrysts were examined to verify the color before mounting for microprobe analysis. The color of small fragments was almost always the same as that determined for the whole megacryst, so the color determinations probably are adequate for the remainder of the collection. The red garnets have a deep red color with no trace of yellow or orange; one megacryst was classified as pink because it is pale and has red tones with no yellow. Orange garnets are pale and have no trace of red. Most garnets (83%; 143 garnets) are red orange. Orange megacrysts are less abundant (13%; 24 garnets), and red megacrysts are the least common (3%; 5 garnets).

Surface features

A number of megacrysts are partly or completely surrounded by a kelyphitic coating, a black to dark-gray microcrystalline aggregate of spinel, phlogopite, chlorite, amphibole, and possibly plagioclase. Kelyphitic rims commonly have a fine-grained, fibrous texture that is radial to the garnet surface. The kelyphite on the garnet megacrysts varies in thickness from a thin plating on the surface to a shell 1–2 mm thick. Megacrysts were tabulated as kelyphite-bearing if a visual estimate indicated that 25% or more of the surface was covered by kelyphite; 38% (68) of the collection met this criterion.

Embayments are distinct concavities in the outer surface of the garnet, which range from slightly rounded square or rectangular holes to blocky or tabular shapes extending well into the megacryst. The blocky and tabular embayments closely resemble the shapes of euhedral crystals, and a few suggest prismatic pyroxene crystal forms. Inner surfaces of the embayments are covered with kelyphite or kimberlite matrix, or they are smooth and straight with nothing adhering to them. A total of 41 garnets in the

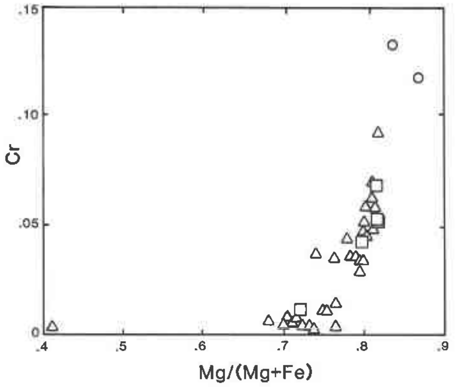

Fig. 4. Cr vs. Mg/(Mg + Fe) diagram for Williams garnet megacrysts. Circles = red garnets; squares = orange garnets; triangles = red-orange garnets.

collection have embayments; several megacrysts have more than one embayment.

Analysis of samples

Physical characteristics were used to select a representative group of megacrysts for analysis. Initially, 10 of the largest (>2 cm), 10 of the smallest (1.0–1.1 cm), and 10 close to the average size (1.6–1.8 cm) were selected. Within the size groupings, garnets were selected to represent the three color groups and the presence or absence of kelyphite and embayments. Some megacrysts that had been previously analyzed by F. R. Boyd (Hearn and Boyd, 1975) were reanalyzed, and some additional megacrysts were selected to ensure that each physical characteristic observed in the collection was represented in the analyzed samples. In all, 44 megacrysts were analyzed.

Analytical techniques

The megacrysts were analyzed with an ARL-SEMQ electron microprobe operating at 15 kV and 0.1 μA beam current with count times of 20 s. Data were reduced on-line using the program $ANBA (McGee, 1983), with Bence and Albee (1968) correction procedures as modified by Albee and Ray (1970). Natural standards were used for all elements analyzed, and a garnet from Kakanui, New Zealand (USNM 143968), was used to check the standardization before analyzing the garnet megacrysts. Oxide totals between 98.00 and 102.00% were accepted, and three to eight analyses were averaged for each megacryst. Analyses were done on small fragments that were broken off the megacrysts and mounted in epoxy. In addition, a polished thin section of one megacryst was analyzed at 0.5-mm intervals along two perpendicular traverses.

Analytical results

The megacrysts are fairly restricted in composition; with one exception, they are pyropes with 59–77% Mg component, 10–27% Fe component, and a small range of Ca component, 6–15% (Fig. 3). The exception is an Fe-rich megacryst, P64-40H-1, which was originally analyzed by Boyd (Hearn and Boyd, 1975) and was reanalyzed during this study with the same results. No other megacrysts in this study are close to the composition of this one Fe-rich sample. Although the small- and large-size groups each appear bimodal in Ca-Mg-Fe composition, the medium-size group covers the whole range (Fig. 3).

Cr contents of the megacrysts are low, ranging from 0 to 2.4 wt% Cr_2O_3; most contain less than 1.5 wt% Cr_2O_3. The most Mg-rich garnets tend to be higher in Cr (Fig. 4). Ca contents of the megacrysts are 4.0–6.0 wt% CaO, and most plot in the low-Cr, variable-CaO region of the

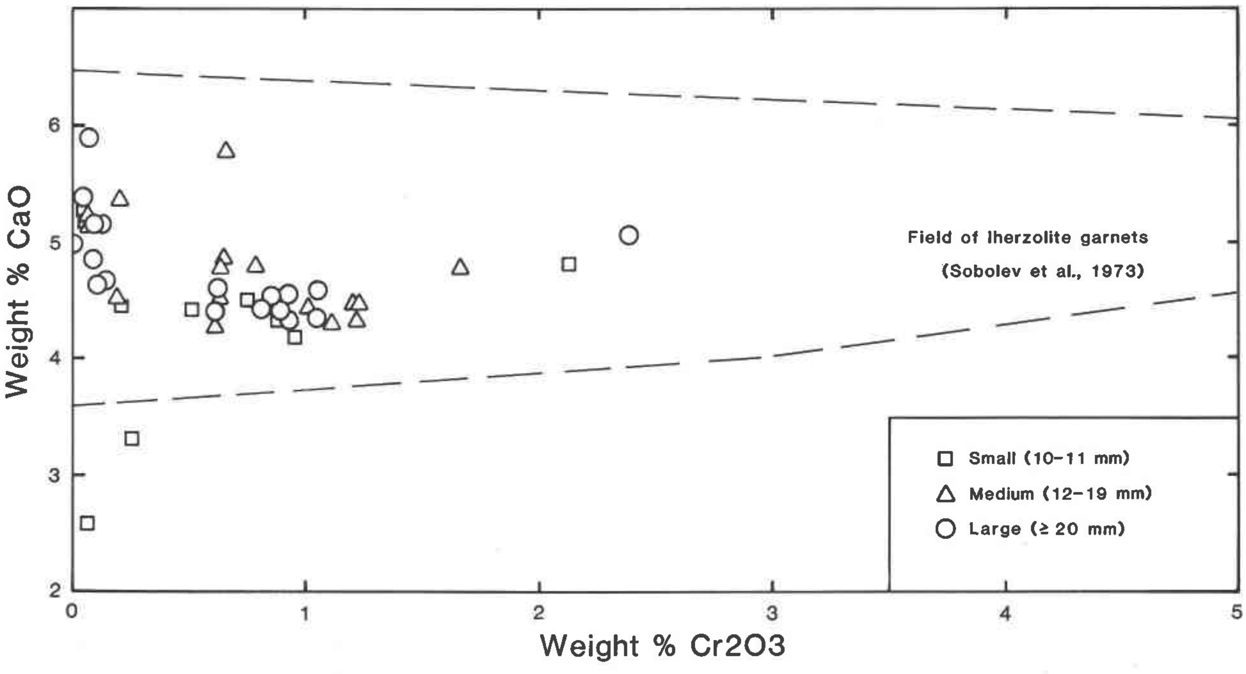

Fig. 5. CaO vs. Cr_2O_3 diagram for Williams garnet megacrysts.

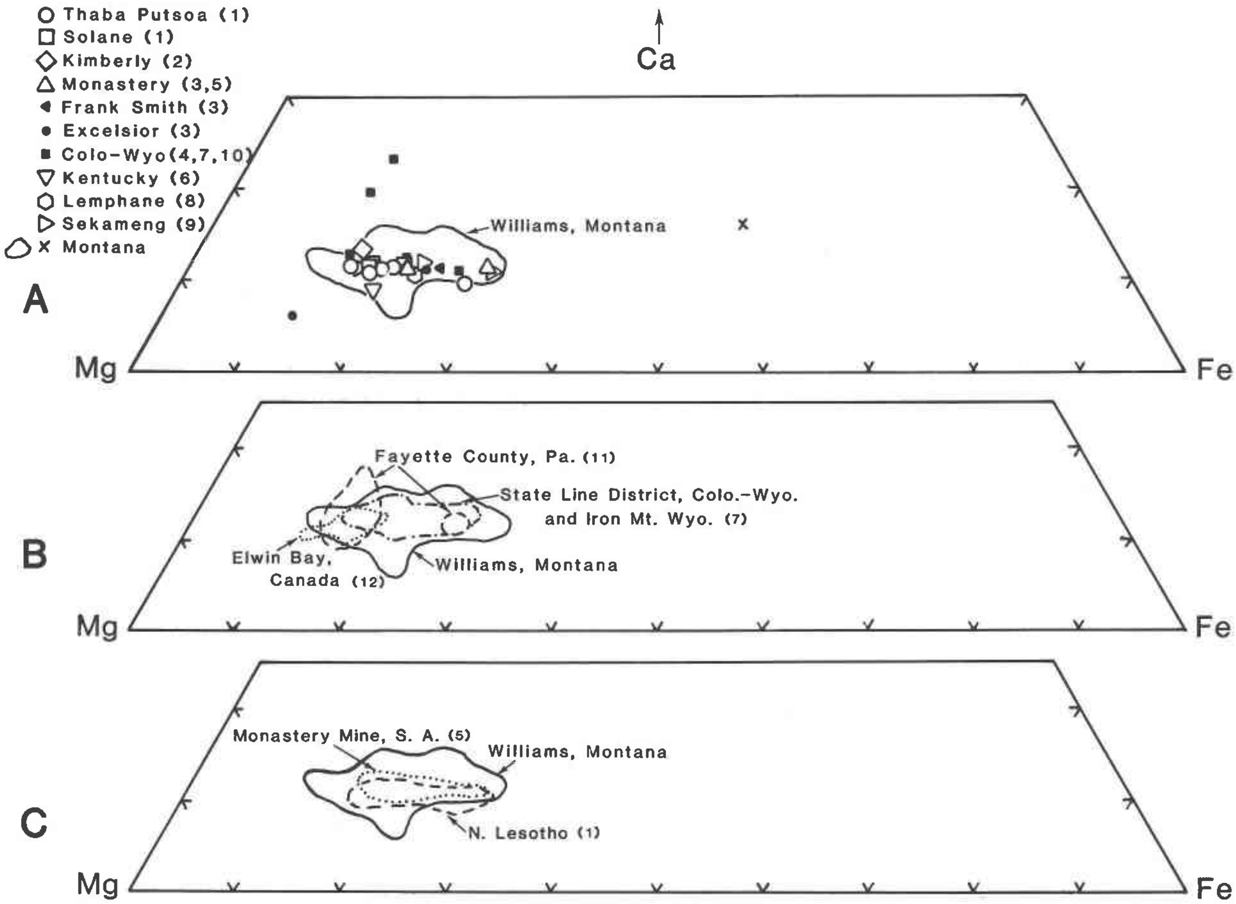

Fig. 6. Ca-Mg-Fe ternary diagram for garnet megacrysts from various kimberlite localities. The field of Montana garnet megacrysts is compared with (A) individual localities in Africa and North America; (B) fields for garnet megacrysts from North America; (C) fields for garnet megacrysts from Africa. References as follows: (1) Nixon and Boyd (1973a); (2) Nixon et al. (1963); (3) Boyd and Dawson (1972); (4) Eggler and McCallum (1976); (5) Gurney et al. (1979); (6) Schulze (1982); (7) Eggler et al. (1979); (8) Kreston (1973); (9) Nixon and Boyd (1973b); (10) McCallum et al. (1975); (11) Hunter and Taylor (1984); (12) Mitchell (1978).

lherzolitic trend of Sobolev et al. (1973) (Fig. 5). No Williams megacrysts have the Cr-rich, Ca-poor compositions that are typical of part of the garnet xenocryst population from diamond-bearing pipes (Gurney and Switzer, 1973). The two garnets that contain less Ca are TiO_2-rich: 0.96 and 1.29 wt%. Most of the megacrysts contain 0.5–1.0 wt% TiO_2, but the total range observed is 0–1.5 wt% TiO_2. Na and Mn contents of the megacryst garnets are very low and fairly consistent: Na_2O is less than 0.15 wt% and MnO is between 0.25 and 0.45 wt% for all except the Fe-rich megacryst.

Although the analyzed fragments were randomly selected, many were from the edges of the megacrysts. A polished thin section of one megacryst was analyzed from core to rim to check for compositional variation. There are no significant variations in composition along two perpendicular traverses. The range of compositions along a traverse is not significantly different from the range observed in the analyses averaged for one megacryst. This indicates that analyses from fragments are representative of the entire megacryst and that the similarities in the compositions of the analyzed megacrysts cannot be attributed to analyzing only fragments from rims.

Comparison with other garnet megacryst suites

The Williams garnet megacrysts are similar in composition to garnet megacrysts from other kimberlites. However, the megacrysts from the Williams diatremes have a range of compositions greater than the compositional range observed in megacrysts from any other individual kimberlite locality. Ca-Mg-Fe compositions (Fig. 6) of garnet megacrysts from other kimberlites in Africa and North America range from 0.75 to 0.60 in Mg component, from 0.13 to 0.29 in Fe component, and from 0.09 to 0.14 in Ca component. All the samples form a concentrated cluster (Fig. 6A) except two Ca- and Cr-rich megacrysts from the Sloan diatreme in Colorado-Wyoming, one Ca-poor, Cr-rich megacryst from Excelsior in South Africa, and the one Fe-rich megacryst from the Williams diatreme.

The Williams garnet megacrysts are all within the low-Cr (Cr_2O_3 < 5 wt%) group of megacrysts described by

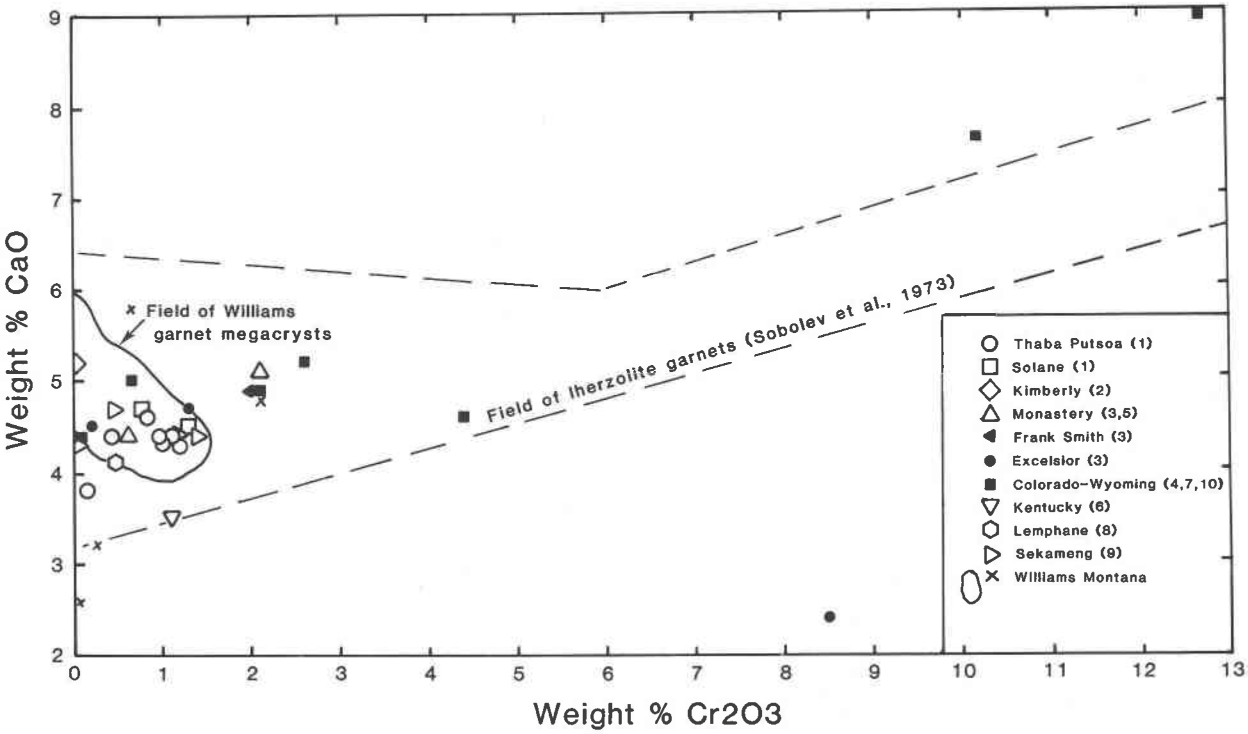

Fig. 7. CaO vs. Cr_2O_3 diagram for garnet megacrysts from specified kimberlites in Africa and North America. References are listed in Figure 6.

Eggler et al. (1979). CaO and Cr_2O_3 compositions for megacrysts from other kimberlites (Fig. 7) are also clustered (with the three exceptions noted above), and the Williams garnet megacrysts are compositionally similar to the majority of megacrysts from other localities.

Correlation of characteristics

One purpose of this study was to determine if correlations exist among the physical characteristics and between physical characteristics and chemistry of the megacrysts. Megacrysts were grouped by their physical characteristics as follows: three size groups (small = 10–11 mm, medium = 12–19 mm, large = 20 mm or greater); four shape groups (disks, spheres, blades, rods); three color groups (red orange, orange, red); two groups for kelyphite (presence or absence); and two groups for embayments (presence or absence). Table 1 is a summary of the characteristics and the distribution of the megacrysts within the various groups. Partial megacrysts, which are 25% of the collection, are not unique in their physical characteristics and do not affect the distribution of garnets within the groups. The Williams garnet megacrysts are rather homogeneous; the majority belong to the medium, disk, and red-orange groups.

There are no strong correlations between pairs of physical characteristics. Bivariate plots and visual comparison of the distribution of individual garnets within groups show no correlations between the groups. The lack of obvious correlations between pairs of characteristics indicates that more sophisticated factor analysis would be unlikely to strongly separate characteristics.

Correlations of composition with physical characteristics are slight because there is little compositional variation from one group to another (Table 2). Color is the only physical characteristic that correlates with composition. The red garnets contain more Cr than the other color groups and belong to cluster group 9 of Dawson and Stephens (1975). Red-orange and orange garnets belong to cluster group 1, as do all the other groups, and do not have distinctive compositions.

The collection studied is large enough to truly represent the garnet megacryst population at the Williams diatreme, and the analyzed megacrysts adequately represent each of the physical characteristics. Although the lack of strong correlations could be due to the relative homogeneity of the collection, no unique physical characteristics were observed for the one megacryst which is anomalously high in Fe. Comparisons of physical characteristics and compositions are significant because they show that only color is a useful indicator of composition.

Origin of the Williams garnet megacrysts

The composition and the physical characteristics of the megacrysts are useful indicators of the conditions of origin of the megacrysts. They suggest that the garnet megacrysts originated in a region of the upper mantle under conditions similar to those that formed the garnet peridotite xenoliths at the Williams diatreme. The Cr-bearing py-

Table 1. Summary of physical characteristics[1]

Group	Criterion		All megacrysts	Analyzed
Size: small	10-11 mm		23	10
medium	12-19 mm		103	16
large	≥ 20 mm		53	18
Shape: disks	w/l >.67	t/w ≤ .67	96	25
spheres	w/l >.67	t/w ≥ .67	25	7
blades	w/l ≤.67	t/w ≤ .67	37	7
rods	w/l ≤.67	t/w ≥ .67	21	5
Color: red-orange			149	36
orange			24	5
red			5	2
Surface: kelyphite	>25% of surface		68	16
embayments	rect.-square cross section		41	18

[1]More detailed information available on request from the author.

ropic compositions of the garnet megacrysts are typical for garnets from the upper mantle. The distinctive shapes of embayments in many of the megacrysts suggest the presence of other minerals that most likely formed in equilibrium with the garnet. One embayment contains a remnant clinopyroxene that has Ca/(Ca + Mg) of 0.371, indicating formation at a high temperature. Two clinopyroxene inclusions in another megacryst also have high Ca/(Ca + Mg) (0.371 and 0.364). Temperatures of equilibration of 1310–1330°C were calculated for the three clinopyroxenes with the thermometer of Lindsley and Dixon (1976) and the TEMPEST program of Finnerty and Boyd (1984). The temperatures are in good agreement with the temperatures calculated for the high-temperature and high-pressure xenolith group from the Williams diatreme (Hearn and McGee, 1984), and they imply a depth of origin of about 150–190 km.

The range of Mg/(Mg + Fe) values (0.78–0.88) in the megacrysts implies derivation from a series of fractionated liquids in the upper mantle. Garnets in peridotite xenoliths from the Williams diatreme have a restricted range of Mg/(Mg + Fe) values (0.78–0.88) and range in size from 0.2 to 5 mm (Hearn and McGee, 1984) so it is unlikely that the garnet megacrysts are from fragmented peridotite xenoliths. Embayments and inclusions in the megacrysts indicate that less abundant and relatively finer grained phases coexisted with the garnets during crystallization. Fracturing in the megacrysts is probably due to thermal stress during kimberlite ascent or emplacement. The predominance of disk shapes among the megacryst group indicates that the megacrysts experienced planar fracturing, either in the source region or during ascent of the kimberlite.

The similarity of the Williams garnet megacrysts to garnet megacrysts from other, widely scattered kimberlites implies that the conditions that form garnet megacrysts must be similar worldwide. Garnet megacrysts from the Williams kimberlites show that megacrysts from a single locality can have as large a compositional range as megacrysts from several localities combined. Comparison of composition with readily observable physical characteristics for a large group of megacrysts shows that color is the best indication of composition. Purple to red garnet megacrysts are likely to be more Mg- and Cr-rich than orange ones.

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Table 2. Average compositions for size and color subgroups[1]

	Small [10]	Medium [16]	Large [17]	Red [2]	Orange [5]	Red-orange [35]
SiO_2	41.95(.61)	41.94(.36)	41.96(.40)	42.76(.52)	41.85(.43)	41.85(.37)
TiO_2	.79(.43)	.69(.27)	.70(.19)	.32(.16)	.53(.07)	.79(.26)
Al_2O_3	22.34(.31)	22.37(.48)	22.19(.37)	22.05(.54)	22.61(.25)	22.21(.30)
Cr_2O_3	.58(.64)	.75(.47)	.63(.60)	2.25(.18)	.81(.38)	.55(.45)
FeO	10.07(2.07)	9.91(1.54)	10.65(2.20)	6.70(.98)	9.50(1.83)	10.59(1.78)
MnO	.32(.05)	.32(.04)	.35(.06)	.28(.01)	.32(.06)	.34(.05)
MgO	20.08(1.40)	19.93(1.05)	19.56(1.45)	21.64(.70)	20.50(1.24)	19.63(1.25)
CaO	4.40(.95)	4.74(.43)	4.71(.32)	4.93(.17)	4.34(.13)	4.64(.58)
Na_2O	.07(.03)	.08(.03)	.09(.02)	.05(.01)	.07(.01)	.09(.03)
	100.64	100.73	100.99	100.98	100.87	100.69

[1]The Fe-rich megacryst was not included in these calculations.
[ ] = number included in average
( ) = standard deviation

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